Title:
Knowledge-based Engineering: A Design for X Tool to Increase Designers Sustainability Awareness

Authors:
Federica Cappelletti, f.cappelletti@pm.univpm.it, Ancona, Università Politecnica delle Marche
Marta Rossi, marta.rossi@staff.univpm.it, Ancona, Università Politecnica delle Marche
Luca Manuguerra, Ancona, l.manuguerra@staff.univpm.it, Ancona Università Politecnica delle Marche
Michele Germani, m.germani@univpm.it, Università Politecnica delle Marche

Keywords:
Knowledge-based engineering, Design for environment, Design for X, Design rules, Sustainability index

DOI: 10.14733/cadconfP.2022.38-43

Introduction

In the present market, CAD and CAM represent considerable tools to achieve better design and optimize the manufacturing phases. At the present-day manufacturers are aiming to produce customized high-quality products, with little lead-time, and at reduced costs [5].

The conventional CAD/CAM tools are developed to meet the general needs of the market, but not the rapid or specific requirements of the market or customer. Consequently, the companies are looking to customize or tailor these tools to improve their effectiveness. Among these strategies, one is the application of knowledge-based engineering (KBE) in commercial CAD/CAM systems. KBE is applied to automate repetitive design tasks favoring time savings, enabling designers to explore a larger part of the design space during the various design phases [12].

Numerous approaches and methodologies have been developed [8];[6]; they are generally universal, but sometimes they focus on specific, narrow substantive or scope context [9]. Mainly oriented in the optimization of several general aspects, e.g. assembly, manufacturing, some of them are focused on specific aspects, e.g. casting [2].

Despite these achievements, more effective and efficient application of KBE in industry still encounter various difficulties, both in the process of its application development and in conducting their further development. Difficult in structuring of modelled engineering design knowledge represents one of the main barriers [9] together with difficult in favoring the knowledge reuse [12].

Furthermore, the difficult to address emerging knowledge issues, e.g. environmental issue, which is at today, not faced by available KBE approaches. When the environmental sustainability issue is analyzed in correlation with CAD tool, data integration is the only question faced.

Research interests in integration of CAD and Life Cycle Assessment (LCA) tools are in fact growing. Methodologies and frameworks were proposed and several studies were implemented with commercial or prototype solutions. Data Exchange between CAD and LCA plays a vital role in integrating progress [3]; Fang et al. [1] presented an approach for the machine design and analysis within the CAD/CAE environment, as well as Landi et al., [6] aiming at integrating simulation results and environmental data. Russo and Rizzi [10] proposed a computer-aided methodology based on the integration of Structural Optimization and Life Cycle Assessment (LCA) tool, Tao et al., [11] proposed a life cycle modeling approach based on feature mapping scheme between product, operation and inventory to address the discrepancy in the principles of the utilized methodological approaches of LCA and CAD/CAE and enable data transformation between CAD/CAE and LCA models.

Two main limits therefore emerge: on the KBE side, the need to include new important design drivers, such as the environmental sustainability and an increasing support to the knowledge reuse to improve and support design activities; regarding the integration between CAD and environmental aspects, the focusing on the capitalization of knowledge, absent at today.

The present paper will face these two limits proposing a method to support designers in the optimization of environmental sustainability aspects of their products, through a KBE approach. It allows the identification of design criticalities under the environmental issue, and on a life cycle perspective, supporting designers in their activity and favouring the knowledge use. [11].

Main idea

The methodology aims to advise the designer by identifying possible design errors. The goal is to make a link between the design rules aimed at sustainability with the 3D CAD capabilities developed during the engineering design process of parts or assemblies. The Design for Environment (DfE) rules are applied, with particular interest in product End of Life (EoL) and disassembly. The goal of this tool is to make designers aware of the sustainability of their choices made in the design phase. Fig. 1 shows the inputs and outputs of the developed methodology.

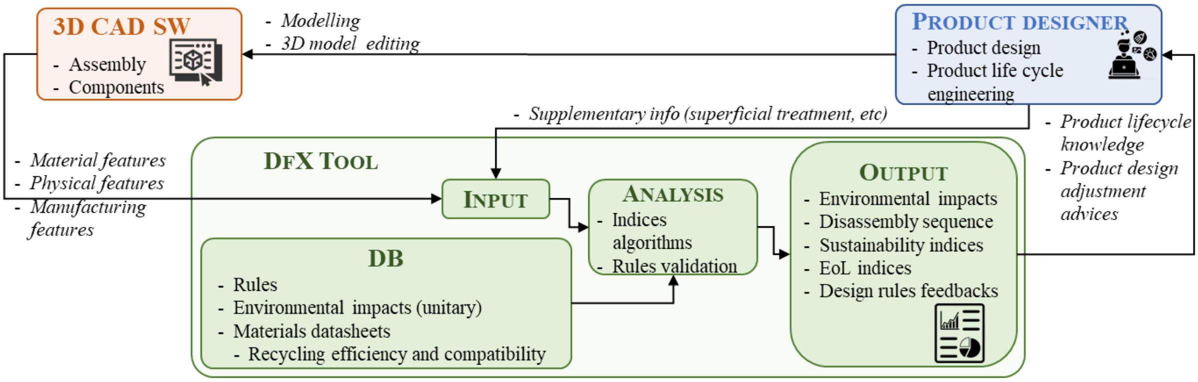

Fig. 1: Methodology.

The workflow is divided into four main steps:

- 3D CAD model: The starting point is the 3D CAD model of the part or assembly
- Recognition and extraction of characteristics: In this phase the 3D CAD model is analyzed, and the recognized characteristics are divided into three main categories: material characteristics, physical characteristics and manufacturing characteristics.
  The information obtained will be used for comparison with the DfE and Design for disassembly (DfD) design rules.
- Analysis: This step allows to verify the design rules against the analysis of the features contained in the 3D model. To make this comparison possible it is necessary to have defined a framework, consisting of a database of rules (DB), mathematical equations, indexes, algorithms and recognition of the functionality of the 3D CAD model. Mathematical equations, indexes, and algorithms are used to verify the compliance of design guidelines retrieved from the literature or company knowledge with information from 3D model data. At the end of the analysis, a report is generated; this summarizes the validated target design (DfX) rules and the identified criticalities.
- 3D CAD model update: In this phase the designer, through the design suggestions coming from the tool and report, modifies the 3D model. Each design guideline recommends the type of design action to be implemented, how the design guideline improves the sustainability of the part, and an illustrative purpose image shows how the rule can be implemented. The feature recognition allows to highlight within the 3D model the specific features that do not comply with the rules in order to facilitate the introduction of the design modification. It is up to the designer to choose whether to implement the proposed design changes, and if so, a new

analysis is performed to check if the updated 3D model complies with the requirements. If there are still unapproved rules, the tool points out the need for further revision of the project. Therefore, an iterative flow is proposed.

The methodology introduced is based on the recognition of the characteristics of the models. A feature recognition procedure begins by defining the types of features to be identified. In general, it is possible to identify the following features:

- The manufacturing feature indicates a feature that consists of a series of related faces and properties. Some examples of product manufacturing features are holes, threaded holes, fittings, chamfers, milling features, turning features.
- The material feature also contains the information related to it
- The physical characteristics feature indicates the dimensions of the part or assembly (volume, area, shape, etc.).

By combining information from the features of the same part, it will be possible to know, for example, the transport limits, therefore the maneuverability of a part, or if a certain feature is feasible in relation to the material considered or if it is accessible in relation to the other features always belonging to the same part. Instead, by relating the features of two different parts within the same assembly, it is possible to determine the connection mode chosen between the two components. This will allow to obtain useful data to understand the assembly strategy and consequently provide a recommended disassembly strategy. The latter will be chosen in relation to the sustainability principles related to the disposal of a product, such as the compatibility between recycled materials.

The output of the analysis, which consists in communicating the compliance with a rule can be divided into different levels of importance: a “Warning” outlines an error that generates potential problems or complications during the EoL or disassembly; while an “Information” is a suggestion that would be desirable to improve the EoL or disassembly process.

Application

Based on the proposed methodology, a prototype version of a DfX tool is developed. It was applied in a case study of an Italian manufacturer of professional espresso coffee machines. Fig. 2 (a) shows the modelling of 3D CAD model of the product. The machine is a complex product, composed of 16 main assemblies and about 900 components. Materials employed must comply with functional and legislative constraints (i.e. contact with food, etc.). In the traditional design process, designers were used to attribute the material to each component but were not able to obtain immediately the classification of the materials employed. This is possible with the DfX tool Fig. 2 (b).

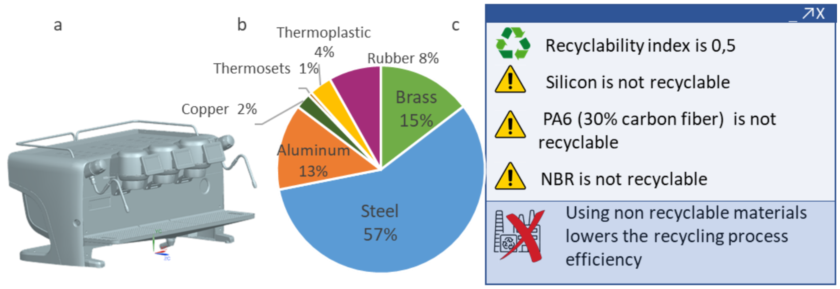

Fig. 2: Analyzed espresso coffee machine (a), material classification (b), output (c).

In accordance to the methodology, the 3D CAD software is the source of all information regarding geometry (i.e., volume, area) and material of the components and assemblies. Those are then related by DfX DB and the necessary information is extracted. Together they constitute the input to the analysis. In the current application, the classification of the materials and the recyclability index were calculated. The materials' classification is extremely important to estimate the quality and quantity of the material scraps (i.e., to be valued by dismantlers), while the recyclability index compares (from an environmental point of view) recycling to different EoL strategies, as suggested by Huysman et al. [4].

Eq. 1 shows the index formula; the algorithms of DfX tool implement the calculation, scales appropriately the unitary values (Tab. 1):

$$Recyclability_{index} = \frac{\sum_{j=1}^{P}\sum_{i=1}^{N} m_{recyc,i}\ RCR_{ij}\left(V_{n,ij} + D_{n,ij} - R_{n,ij}\right)}{\sum_{j=1}^{P}\sum_{i=1}^{N} m_{i,j}\, V_{n,ij} + M_n + U_n + \sum_{j=1}^{P}\sum_{i=1}^{N} m_{i,j}\, D_{n,ij}}$$

Where:

- $D_{n,ij}$ (environmental impact for disposing 1 kg of i^{th} material of j^{th} part) [unit/kg]
- $V_{n,ij}$ (environmental impact for producing 1 kg of i^{th} material of j^{th} part) [unit/kg]
- $R_{n,ij}$ (environmental impacts of production of 1 kg of i^{th} recycled material of j^{th} part) [unit/kg]
- RCR_{ij} (recycling index of i^{th} material of j^{th} part)
- M_n (environmental impact of production of j^{th} part [unit])

Unit is related to the environmental indicator chosen; in this case it is Climate Change and unit is kg CO_2eq. The maximum value of the index is 1; it can be negative when recycling is not convenient. The overall recyclability index for the espresso coffee machine is equal to 0.5.

Material Class	*Brass*	*Steel*	*Alluminum*	*Copper*	*Plastics*			
Materials					Plastics	Thermosets	Thermoplastics	Rubber
Recyclability	Yes	Yes	Yes	Yes		No		No
Biodegradability	No	No	No	No	No	No		No
Dn,ij [kg CO_2eq /kg]	0,761	0,0043	0,761	0,761	0,699			
Vn,ij [kg CO_2eq /kg]	6,88	2,12	9,99	8,21	5,64			
Rn,ij [kg CO_2eq /kg]	0,0738	3,2	0,34	0,0738	1,27	3,56	0,18	1,9
RCRij	0,999	0,995	0,999	0,999	0,767			
Mnj [kg CO_2eq]	1,235	1,2	0,404	0,456	1,3			
Mn [kg CO_2eq]	4,605	47	11	2	10			

Tab. 1: Database information for the espresso coffee machine.

Fig. 2 (c) shows examples of outputs: recyclability index, warnings about the materials whose selection hampers the recycling process. The coffee machine includes components made of non-recyclable materials; they are mostly plastic material, such as: PA6 (Poliammide 6, 30% carbon fiber), NBR (nitrile rubber), EPDM (Ethylene-Propylene Diene Monomer), etc… Although low in weight, these should be avoided or minimized. When their use is required by functional constraints, their disassembly should be evaluated and made possible.

Conclusion

The present work introduces a tool intended for target design, able to couple the potentialities of 3D CAD modeling software and strengthen the environmental awareness of designers. The DfX tool extracts geometrical, shape and feature information of a 3D model and correlates them with a DB. This contains both details about materials and a set of rules to be verified to prove the quality of the design. In the current application, where a 3D model of a professional coffee machine is analyzed, the tool conducted the classification of the materials employed in the product and the calculation of the recyclability index. The index for the whole coffee machine is 0.5, for Climate Change indicator. This reveals that the coffee machine, although being complex, has great potentialities to be recycled. It is composed up to 90% in weight of recyclable materials, whose recycling process is less impacting than other EoL strategies (i.e., landfill).

Three are the main potentialities of the proposed tool:

- It can be used both prior to and after designing: whenever it is used during the part or assembly modeling the designer can receive feedbacks about the product design and future performances (manufacturing, EoL, environmental, etc.) each time the analysis is launched, and it will be updated every time; on the contrary, designer can launch the analysis at the end of the design and verify whether it fulfills all the rules and to obtain a forecast of the product performances;

- It includes new important design drivers and a support to awareness of designers: designers may be extremely expert of the product and its functionalities, but may lack of knowledge about sustainability, EoL strategies, maintenance, etc. This tool allows them to obtain feedbacks and simplified forecasts, and thus to introduce innovative targets in the design process;
- The database can be update, both with conventional knowledge and with specific input; for example, any information deriving from product maintenance, use, or EoL phase may generate new design rules to verify or additional KPIs to evaluate (the latter would require further algorithms development).

The recyclability index of materials should be incorporated in the evaluation and optimization of disassembly and design for disassembly. The trend, mostly dictated by legislation, is that materials should be recycled so that once again new products can be produced from those recycled materials. The recyclability index evaluated in the case study refers to a completely disassembled product. Therefore, it becomes important to consider not only the potential recyclability index of materials but also how luckily their conditions are satisfied; in other words, the disassembly is necessary together with its optimization in order to ensure that materials can be recovered. Future works will thus focus on the disassembly analysis and how the link with the 3D CAD model can simplify the analysis.

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